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NAVY ADDITIVE MANUFACTURING: POLICY ANALYSIS FOR FUTURE DLA MATERIAL SUPPORT

December 2014

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NAVY ADDITIVE MANUFACTURING: POLICY ANALYSIS FOR FUTURE DLA MATERIAL SUPPORT

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LIST OF ACRONYMS AND ABBREVIATIONS

3D	Three Dimensions or Three Dimensional
3DP	3D Printing
AM	Additive Manufacturing
AMDO	Aviation Maintenance Duty Officer
AS	Submarine Tender
CAD	Computer Aided Design (Modeling)
CDSA	Combat Directions Systems Activity
CNO	Chief of Naval Operations
CONUS	Continental United States
COTS	Commercial Off The Shelf
CRIC	CNO Rapid Innovation Cell
CT	Computed Tomography
CVN	Aircraft Carrier (Nuclear)
DLA	Defense Logistics Agency
DOD	Department of Defense
EBM	Electron Beam Melting
EDO	Engineering Duty Officer
ELM	Mobile Expeditionary Labs
FDM	Fused Disposition Modeling
FLC	Fleet Logistics Center
FOB	Forward Operating Base
FRC	Fleet Readiness Center
HAZMAT	Hazardous Materials
IDIQ	Indefinite Delivery/ Indefinite Quantity
IP	Intellectual Property
JHSV	Joint High Speed Vessel
LENS	Laser Engineered Net Shaping
MILSPEC	Military Specifications (Standards)
MRO	(Facilities) Maintenance, Repair and Operations
MSC	Military Sealift Command

N41	OPNAV Directorate for Logistics Programs & Business Operations
NAMTI	Navy Additive Manufacturing Technology Interchange
NAVAIR	Naval Air Systems Command
NAVSEA	Naval Sea Systems Command
NEC	Navy Enlisted Classification
NAWC	Naval Air Warfare Center
NSWC	Naval Surface Warfare Center
NUWC	Naval Undersea Warfare Center
NWDC	Naval Warfare Development Command
OEM	Original Equipment Manufacturer
OCONUS	Outside the Continental United States
ONR	Office of Naval Research
OPNAV	Office of the Chief of Naval Operations
PBF	Powder Bed Fusion
PTF	Print The Fleet
RDT&E	Research, Development, Test and Evaluation
REF	Rapid Equipping Force
SLA	Stereolithography
SLS	Selective Laser Sintering
STL	CAD file used to build parts (from STereoLithography)
SYSCOM	Systems Command
UAS	Unmanned Aerial System
USN	United States Navy
UV	Ultraviolet
VTOL	Vertical Takeoff and Landing
WRNMC	Walter Reed National Medical Center

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This paper would be pure conjecture if it were not for the help of a number of subject-matter experts on Navy AM. Pete Norgaard provided me with the seed corn of my research while we were colleagues at CNO Strategic Studies Group. Dave Barrett at OPNAV N415 introduced me to the treasure trove of information at Navy Additive Manufacturing Technology Interchange. Ben “Prof” Kohlmann at the CNO Rapid Innovation Cell enlightened me on the current state of AM testing afloat. Dr. Paul Hess at the Office of Naval Research gave me valuable pointers on AM research in the Navy. Jim Lambeth at Combat Directions Systems Activity, Dam Neck laid out for the novice the obstacles to AM adoption. Bryce Weber at Naval Undersea Warfare Center, Keyport collected very valuable information from his colleagues on the variety of AM uses and provided great ideas on how it could be supported on a larger scale.

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I. INTRODUCTION

A. OVERVIEW

The U.S. Navy has a massive appetite for parts. It is a service defined by its machinery—ships, planes and submarines, and has technological roots reaching back hundreds of years. Sail ships did not have mechanical parts per se, but they were dependent on materials for construction and upkeep, as modern platforms are today. In the age of steam and steel, machine shops replaced carpenters onboard ships to fabricate some parts instead of relying on the supply chain to provide them. In the modern technological area, the Navy has become more dependent on the supply chain, thanks to parts too complex to machine, but this is about to change.

Additive manufacturing (AM) systems (commonly known as "*3D printing*") could bring the organic parts manufacturing capability back to deployed units, but the Navy and the Department of Defense (DOD) has to adopt this technology first ashore and determine how best to support it before making the crucial step aboard. This first adoption stage has already started. More than 20 Navy organizations use AM systems, employing 35 different models of differing types and modalities (Navy Additive Manufacturing Technology Interchange, 2014)**.** These are largely used in the niche role of prototype construction and custom part manufacturing, but they are also part of a research into the technology itself for its suitability in a multitude of systems and processes.

Chief of Naval Operations (CNO) designated Deputy Chief of Naval Operations for Fleet Readiness and Logistics (OPNAV N4) as the Navy Lead for Additive Manufacturing (AM) "to develop, deconflict and manage" (OPNAV N41, 2014, p. 3) this technology within in the Navy. To continue this work, the Navy Additive Manufacturing Technology Interchange (NAMTI) Charter was signed in October 2014, giving that organization the mission to "to advocate for and facilitate the introduction of AM into the Department of Navy infrastructure and logistics processes" (OPNAV N41, 2014, p. 4).

Led by OPNAV N41 and the Office of Naval Research, NAMTI will be a governance structure to future expansion of AM throughout the Navy.

This technology adoption is not happening in a vacuum. The other services have AM systems in operation, but currently lack the organizational structure that the Navy has developed for this investigation. Private industries, including government contractors, have been using AM systems far longer than any DOD entity. Since this technology will change how the parts supply chain will look in the near future, the Defense Logistics Agency (DLA) will be an important stakeholder going forward, for the supplies needed to manufacture these parts on a global scale will have to be provided to where AM systems are deployed.

The potential for this technology for the USN is significant. If AM is adopted across the fleet and shore facilities, the Navy could drastically shorten lead time for parts shipment or eliminate it completely, keeping operational availability higher and giving ships more independence from the supply chain. With our ageing fleet, it could save money by giving units the ability to print discontinued parts and those at the end of their life-cycle, instead of contracting out their manufacture.

In the near future, AM could imbue ships with capabilities that enhance the human capital of the Navy through “maker culture;” new systems and capabilities could be manufactured on deployed assets to adapt to emerging threats and challenges. This happens at the niche level ashore now, so this possibility is not remote. How quickly this capability can be diffused and how it can be supported are the questions that need to be asked now in order to make this future world happen.

B. CASE STUDY ANALYSIS

This fact-finding research project will examine the technology adoption chain perspectives of Additive Manufacturing and how it might spread throughout the Navy from its niche usage to widespread adoption. In order for this technology to be adopted in an efficient manner, its value has to be proven to each command down the chain for uniform usage. Additionally, Navy Systems Commands will have to be onboard with the technology and its benefits in order to fund it. Even though there are other possible

transmission paths, top-down input could lead to common AM machines throughout the Navy, leading to economies of scale in acquisition and supply. Navy activities are already testing the technology on several levels; their results could provide helpful indicators of the AM challenge that faces the Navy and DOD as a whole.

C. RESEARCH QUESTIONS

The focus of this study is this: how should DLA best support AM efforts in the Navy in order for the Navy to achieve its goals using 3D printing? What is the most cost effective method or the one that is most in tune with how the DLA currently supports the Navy and DOD as a whole?

To answer this question one first needs to understand who is using 3D printing in the Navy, what for, and how their needs are going to grow in the foreseeable future. Therefore, I also study how AM will spread throughout the Navy, and how fast it may happen.

The initial question in this study is how will AM spread throughout the Navy, and how fast will it do so? AM is rapidly becoming part of the industrial landscape in the civilian world; the demand for machines, related software and materials is expected to rise 21% a year to $5 billion in 2017 (Additive Manufacturing on the Rise, 2014). It still resides largely in niches in the Navy and will face a number of hurdles as it diffuses through different commands, afloat and ashore. As simple as it would seem for a unit to purchase an AM system commercial off the shelf (COTS) and install it in a workshop, the Navy has requirements for supply and certification that have to be met for this to happen.

Adoption of AM will not happen if it is not proven to be cost effective or supportable by the greater supply chain of DLA. Currently, AM is used to build prototypes, fitment parts, visualization models, tooling, fixtures, shop accessories and end use hardware in Naval Systems Command depots and warfare centers (B. Weber, personal combination, September 16, 2014), along with custom medical devices at Walter Reed Armed Forces National Medical Center (Navy Additive Manufacturing Technology Interchange, 2014). This niche works now, for it needs small amounts of parts that built with quantities of materials that are not major expenditures to purchase.

D. SCOPE

This study will look at the adoption chain of AM usage throughout the U.S. Navy. The commands that currently use AM will be examined for the type of AM technology they use and how they employ it for their missions. The diffusion of AM to other commands will then be analyzed to determine how and why others within the Navy and DOD would employ it. Obstacles to widespread adoption will be delineated

E. METHODOLOGY

The research focused on contacting representatives of Navy commands and collecting information on how they use AM, along with their sources of supply. Additionally, information from the Navy-wide NAMTI initiative is used to show the distribution of AM technology and how it could be spread further, through an investigation of the technologies involved.

Vendor information is used to illuminate the potential of the technology in commands that currently do not employ it. If it is considered infeasible to employ in certain commands, potential work-arounds are determined based on current Navy supply chains. An analysis of current usage is used to examine how, if ever, the DLA should stock AM materials in support of Navy and DOD systems.

II. LITERATURE REVIEW

A. NAVAL TECHNOLOGY ADOPTION

Previous research on the topics of AM and technology adoption has been carried out, but the two topics have not been combined into a study examining long term diffusion of AM throughout the Navy and its implications. Life-cycle cost reduction in the Navy with the technology has been examined in depth (Kenney, 2013), but this study looked more at the technical feasibility and the fiscal benefits of AM in specific situations, not Navy-wide.

Previous to that work, a case-study based book, "*Warfighting and Disruptive Technologies*" (Pierce, 2004) went a long way into showing how the "innovator's dilemma" (Christensen, 1997) can be overcome in the military. AM adoption must be studied in a different manner, though, for in either case, survival of a firm (or military) depended on the adoption of the technology, but improper adoption of AM will not lead to the failure of the U.S. Navy. Regardless, it could lead to a much improved Navy if the disruptive tech is absorbed properly.

B. DIFFUSION OF INNOVATIONS

The discussion of the spread of AM throughout the Navy will be framed with Everett Rodgers' work "*Diffusion of Innovations*" (2003). Now in its fifth edition, it has been discussing the idea of the spread of ideas and technology through organizations since 1962. Each diffusion path and mode is different, but they all have the same elements; the innovation itself, the communication channels, time, and the social system it is introduced to. Furthermore, the classes of innovators are broken down into innovators, early adopters, early majority, late majority and laggards. Individuals will choose to adopt a new innovation based off of five factors; relative advantage, compatibility, complexity or simplicity, trialability and observability (Rogers, 2003).

Table 1. Rogers' Five Factors (from Rogers, 2003)

Factor	Definition
Relative Advantage	The degree to which a product is better than the product it replaces
Compatibility	The degree to which a product is consistent with existing values and experiences
Complexity	The degree to which a product is difficult to understand and use
Trialability	The degree to which a product may be experimented with on a limited basis
Observability	The degree to which a product usage and impact are visible to others

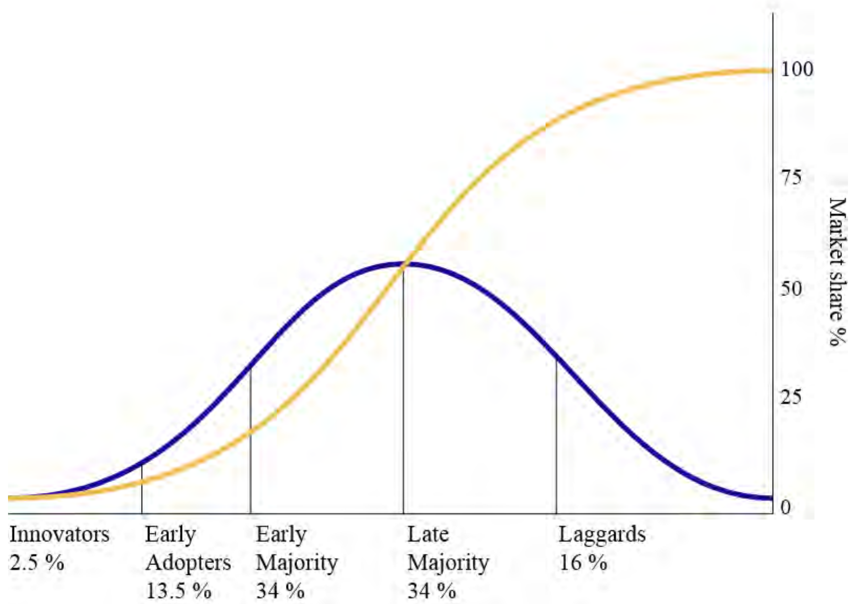

Figure 1. Innovation bell curve (after Rogers, 2003)

Following Roger's work, Frank Bass developed a model to chart this growth in 1967 (Bass, 2004). He consolidated all of the groups following Roger's "innovators" into an "imitators" group that was influenced in the timing of the adoption by the decisions of other members in the system (Bass, 2004). In general, the projections illustrated in this model imply an exponential growth of initial purchases to a peak and then exponential decay, but for that, it needs some sort of replacement technology to take over. The usefulness of this model is that objective determinations can be made based upon

subjective judgment of parameters, but it does not work well for industrial processes, for a new technology is supposed to completely replace the previous one, the way black and white televisions were replaced by the color variety (Bass, 2004).

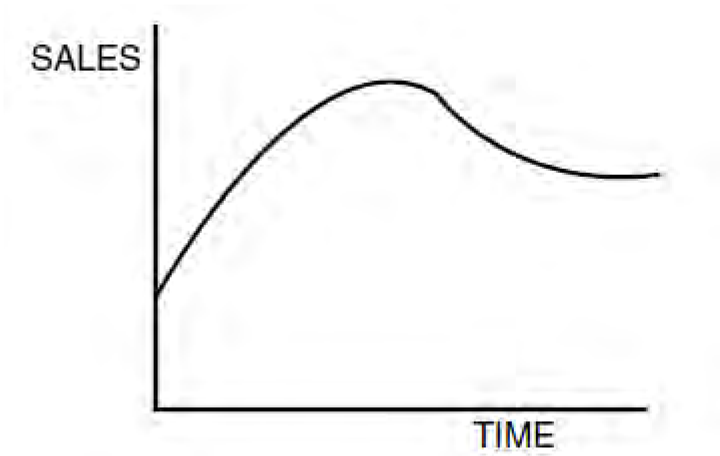

Figure 2. Ideal Bass new product growth curve (from Bass, 2004)

Further developments were the identification of an ecosystem that has to account for in order for organizations to plan for innovation adoption (Adner, 2006). Organizations have to account for collaborations with others in order to mitigate initiative (program management), interdependence (coordination) and integration (uncertainty) risks throughout the value chain of the product. This involves assessing where the benefits to an adoption lie, and if they do not outweigh costs in each step of adoption, the end user will never know its benefit (Adner, 2006). The magnitude of this benefit is not the only factor that matters to decision maker; the location in the chain is equally important (Adner & Kapoor, 2010). Components upstream, downstream and complementary to the location of the innovation have to be ready for it; otherwise it will not be adopted effectively. This brings technology leadership to the forefront, for it is easier to manage inside an organization's ecosystem when the complements to a technology could make or break it.

The adoption of a new technology will have many hurdles to overcome, but there are many ways to minimize resistance to it. Most adoption studies view new innovations

as “products” that are to be sold to customers, and many of them look at how to get customer buy in. For the sake of discussing innovation adoption in the Navy and DOD, the view through a simple lens that the senior leadership is a company and the members of the service are customers works quite well. Many innovations fail because consumers irrationally overvalue the old and companies irrationally overvalue the new (Gourville, 2006), and even though a technology can be forced on members of the military, it does not mean that it will be successfully adopted. Throughout naval history, there was significant resistance on every level to technologies such as steam power, long range rifled cannon, torpedoes, submarines, and aircraft carriers until they proved themselves to be an incredible improvement over what was currently available. This illustrates a simple principle of adoption; if the relative benefits of an innovation are so great that it overcomes any potential losses (that the user tends to overweigh or over exaggerate); the new technology will succeed (Gourville, 2006). The above examples seem to be pretty obvious now, but in some cases that benefit had to be proved in a contest of arms that cost significant blood and treasure before they were adopted wholesale.

Since some technologies cannot be tested in the crucible of warfare, there are other organizational ways to aid adoption related to the behavior change that new technology requires from its users. Gourville puts innovations into four categories of based on a matrix that scales the degree of behavior change needed and the benefit/change that the product imparts; easy sells, sure failures, long hauls, and smash hits. The “easy sell” involves small changes in behavior with minimal benefit. The “sure failure” requires big behavior changes with small benefit. If there is a big benefit but it needs a large change in behavior, a “long haul” approach will be in order. The “smash hit” is by far the most desirable; a large benefit in exchange for a little behavior change (Gourville, 2006). There have been military innovations in each of these categories, and as we will see, AM fits into this schema as a “long haul.”

Even though the Navy is used to “long haul” adoptions, it would still benefit from shortening the timeframe of the process as much as possible by minimizing resistance when and where it can. If an innovation is behaviorally compatible to how users currently operate, it will be adapted easily. “Unendowed” users who do not have the capability that

a new innovation improves or introduces will be more likely to take on that technology. And if a core of believers is cultivated who overvalues the benefits of that innovation is found, they will later introduce it to others (Gourville, 2006), and to cross theories here, will become the cadre of advocates that will lead to further adoption within an organization.

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III. ADDITIVE MANUFACTURING TECHNOLOGY

A. ADDITIVE MANUFACTURING BASICS

"Additive manufacturing" is a term that covers many different technologies that use different methods to build physical items in layers or stages, in automated systems that use 3D Computer Aided Design (CAD) models as their inputs. The final geometry of the item is reproduced without having to adjust for manufacturing processes or paying close attention to tooling, undercuts, draft angles or other features (Gibson, Rosen, & Stucker, 2010). The term "*rapid prototyping*" was used to describe technologies that used digital data to make physical prototypes, but since these methods are now being used for more purposes, including limited production lots, AM is a more effective term (Gibson et al., 2010). Similarly, "*3D printing*" is also used interchangeably with AM, but since it is also used to describe a specific process, this paper will use the acronym "AM" to align with the ASTM International standard terminology (ASTM International, 2012).

Even though AM has reached popular consciousness as of late, it has been around since the 1980s. At that point, computers, lasers, controllers, and other complementary technologies had reached the sophistication point that concepts devised in the 1950s and 1960s could have physical form. The first patents for AM were filed in Japan, France and the U.S. in 1984. One of the U.S. patents was filed by Charles Hull, and that gave rise to 3D Systems, a major player in the industry today (Gibson et al., 2010). By 1989, the four major technologies in use today had been patented; material extrusion, jetting, vat photopolymerization, and powder bed fusion (PBF) (Gibson et al., 2010). In 2012, the ASTM standards for AM identified two additional major techniques; sheet lamination, and directed energy deposition (ASTM International, 2012).

Building items with AM technologies follow eight general steps, regardless of the exact process (Gibson et al., 2010).

1. CAD is used to conceptualize a part on a computer. It could be created in a software program with human interface drafting or using reverse engineering technologies, such as a laser line scanner or computed tomography (CT) scan using X-rays.

2. CAD visualization is saved in the STL file format. This is the standard file type that almost every AM system accepts. It describes the external surfaces of the model and the calculations of the slices that need to me made during part build.

3. STL file is transferred to the AM machine. Some changes might have to be made so that the size, position and orientation of the item is accounted for in the specific machine.

4. AM machine is set up for the build process. Each build might have specific power, material and timing requirements.

5. Item is built. This is largely an automatic process, but supervision is needed to watch for errors or other glitches or interruptions to power or material feed.

6. Item is removed from the AM machine. Safety interlocks have to be removed and the system has to cool in some cases.

7. Postprocessing is done so the part is ready for use. Supporting features might have to be removed, and other cleaning and finishing could be needed. This stage could require experienced and careful manual manipulation, and could require chemicals to harden the part. For some modalities, this could create waste that cannot be reused.

8. The part is prepared so that it has the finishing for use. This could involve priming and painting so that it can fit with other parts. If there are electronic parts that need to be assembled together, this is where they are made until the final product.

In many cases, the next two steps are combined and interchangeable. It is completely dependent on the AM method and what material is used for that specific product. An implied aspect of the finishing for use is the inspection and certification, using manual methods such as calipers or the same techniques used to reverse engineer the design (laser or CT). In some cases, tight tolerances need to be met for an AM-produced item to be used as a replacement part (Lively, 2014). Even then, material properties such as strength, electrical and thermal conductivity, and optical transparency typically have inferior properties due to the anisotropy caused by the layer by layer approach (Ivanova, Williams, & Campbell, 2013). This directional weakness means that the parts cannot be stressed in the same way that a molded or welded part can.

Additive Manufacturing is still a maturing technology. With each coming year, AM systems have been working with more complex materials at higher temperatures, allowing for part builds with titanium and other metals, including composites of multiple materials. One company, Objet (now part of Stratasys), has systems that can print with over 100 materials (McNulty, Arnas, & Campbell, 2012). The exact process of how products are made is also still in flux. New milling (or subtractive) machines have added capability to alternately build up and mill away using a wide variety of metals. This will further expand the capabilities of additive processes from metal prototype and small part production to the complete machining of complex components with undercuts as well as repair work on complex metal parts (Lorincz, 2014). It will also make the parts stronger in multiple directions, reducing the anisotropic weakness described above.

B. NAVY ADDITIVE MANUFACTURING TECHNOLOGIES

The Navy currently operates AM machines in depots, labs, hospitals and other warfare centers. Four major modalities (PBF, material extrusion, vat polymerization and jetting) are represented, with a handful of systems that do not fit these categories. The material extrusion process of fused deposition modeling (FDM) is the most common type in use (Navy Additive Manufacturing Technology Interchange, 2014). This paper will examine these major system types, how they are used, and general advantages and disadvantages when compared to other AM modalities.

1. Powder Bed Fusion

PBF is one of the AM first processes that were commercialized (Gibson et al., 2010). Selective Laser Sintering (SLS) is the earliest form and the terms are often used interchangeably. In SLS (and the related process Electron Beam Melting or EBM), the laser or electron beam fuses heated powder in thin layers that has been leveled by a roller that travels across the build area. As each layer is completed, the build platform lowers, the powder bed is spread and levelled over the previous layer, and the next layer is built on top. This process is carried out in a chamber that is heated to specific temperatures. EBM is a faster and efficient process than SLS, but has a poorer resolution (Niebylski & Rachami, 2013).

Large defense and aerospace contractors focus on PBF processes for their usefulness with high-quality metal allows necessary for aircraft components (Niebylski & Rachami, 2013). The systems are more expensive but produce higher quality outputs than most other AM systems. They are employed by at least seven activities in the Navy (Navy Additive Manufacturing Technology Interchange, 2014). Naval Undersea Warfare Center (NUWC) Keyport has been using a SLS system since 2002, with which it produced over 35,000 parts (Weber, Morris, & Mahoney, 2014).

a. Advantages

PBF is a versatile process. It can use a variety of powders to create products that are made out of polymers, metals, ceramics and composites (Gibson et al., 2010). It can be quite economical in that it does not use material to build supports for the items during builds; this does not waste material nor require additional post processing. After cooling, the part needs to have additional powder cleaned off of it, and it is ready for finishing.

b. Disadvantages

The PBF process depends on environmental stability for the laser or electron beam to work and an uninterrupted supply of powder and electrical power. In most cases, the build chamber is filled with nitrogen and the introduction of oxygen and other gases could distort the laser beam or warp the product as it cools. The AM machine has specific operating tolerances with regard to ambient temperatures and humidity. The chamber has to have enough powder in it to build the part completely, as the process cannot be interrupted. The powder is can be dangerous in itself; it can spread through the air while the machine is being filled or completed items are being removed, and can damage electronic components internal and external to the machine (Gibson et al., 2010). In addition, some airborne powders are explosive in certain concentrations. Finally, the powder has to be heated to a specific temperature for the entire build, so if there is any interruptions to the AM machine’s power supply during the process, the entire part could be ruined.

2. Material Extrusion

Material extrusion is a process by which raw materials are dispensed in layers through a nozzle that moves in the vertical and horizontal axes (Niebylski & Rachami, 2013). FDM, the most widely used AM technology in industrial applications, uses heated material, but there are chemical and gel based material extrusion based technologies that are used in medical applications. In both cases, a nozzle extrudes material that is fed from a preloaded chamber or continuous supply of bulk material in pellet, powder, or filament forms. In the case of FDM, that material is liquefied so that can be pushed through the nozzle, and is kept in a constant temperature until application (Gibson et al., 2010). The material comes out of the nozzle onto a platform that moves in the vertical direction to form individual layers, at the correct temperature to be conductive to bonding between layers and shapes within a layer. FDM systems require supports made of the same or differing material to build upon, for they do not have a bed of material to rest on. After the item is built through successive layers, it is allowed to gradually cool, the supports are removed and it often has to be post-processed with a liquid solution (Gibson et al., 2010).

This process is often used to make concept models by companies in early stages of product development for prototypes, component design and validation. This is the primary reason why 15 different Navy activities employ FDM systems (Navy Additive Manufacturing Technology Interchange, 2014). In the case of NUWC Keyport, three different thermoplastics are used to create functional prototypes before injecting molding tooling in order to test form, fit and function (Weber et al., 2014).

a. Advantages

Material extrusion machines operate with many different material types (including Kevlar) (Gibson et al., 2010), but cannot work with most metal material. FDM systems are the least expensive AM machines and the simplest in form. This is due to the fact that the original patient for the process of FDM expired in 2009, leading to a proliferation of the technology through new start-ups, existing corporations, and open source initiatives (Niebylski & Rachami, 2013). It also is the most stable of the four major processes that the Navy uses, since there is no pool or bed of material that has to be

kept level for the build process. In addition, it can operate with a filament feed, so a large chamber of build material is not needed to make the part.

b. Disadvantages

Most of the disadvantages relating to material extrusion are related to the use of a moving nozzle in the disposition process. This affects the build speed, accuracy and density. The nozzle determines the shape and size of extruded filament; a larger nozzle has faster flow but lower accuracy (Gibson et al., 2010). The nozzles cannot be changed during the specific build process, and have to be cleaned. The material has to flow from the nozzle with the same inertia so that the final part has uniform structural qualities. This means that rapid changes in direction have to be accounted for in the build design and speed, a consideration that a laser does not have to be concerned with (Gibson et al., 2010). This is a major concern if the system is on a moving platform, such as a ship, for the nozzle movement and material flow will be affected by the angular forces from rocking and tilting, which will, in turn, affect the layers of material laid down. The item also has to be built onto supports that are built from the same material, is provided separately or has to be built beforehand using a different input material. This process introduces waste, for that material cannot be reused or recycled. Finally, most FDM polymers have to be finished with chemically induced smoothing or burnishing, necessitating the purchasing of additional materials that could be considered hazardous in some environments.

3. Vat Photopolymerization

Vat photopolymerization is similar to PBF in that material is built in layers out of a pool of material, usually an Ultraviolet (UV) sensitive photopolymer resin. Stereolithography (SLA) was the first commercially patented version of this system, and it is the most common AM modality in this category (Niebylski & Rachami, 2013). Items are built in SLA as a laser, pair of lasers or projected shape (mask) is scanned across the surface of the resin. As the layers are formed, a build platform is moved vertically and a sweeper blade recoats the surface of the liquid resin. Then the next layer is built the

liquid is refilled from as reservoir as needed through the build process (Gibson et al., 2010). The parts are often built upside down.

Six Navy activities employ SLA systems for building prototypes; Walter Reed builds surgical medical models and custom surgical guides with their systems (Navy Additive Manufacturing Technology Interchange, 2014).

a. Advantages

SLA parts have better accuracy, parts finish and mechanical properties than material extrusion parts. This lends their use to building functional prototypes (Gibson et al., 2010).

b. Disadvantages

This process depends on a vat of UV sensitive resin, so it is very limited in the materials that it can use. It has the same stability concerns as PBF, for it depends on a level layer of material to build upon. The 2D build area means that it cannot be built from multiple angles as some jetting and material extrusion processes allow. Photo curable resins tend to warp over time, so it is not useful for parts, only prototypes, and the systems tend to can be large and expensive (Niebylski & Rachami, 2013). Support structures need to be built into the part and removed in post processing, and the part has to be cleaned and cured afterward, a very labor intensive process (Gibson et al., 2010).

4. Jetting

This process is sometimes called 3D printing (3DP) for it is a direct offshoot of inkjet paper printing. There are two subtypes to his modality that both involve depositing droplets of liquid material in layers. The first is material jetting, which uses an inkjet head to move across a print area and deposit a polymer or wax in layers. The second is binder jetting, where the head puts down layers of material onto a bed of powder that is then shaped into the desired objects, an almost combination with PBF (Niebylski & Rachami, 2013). If UV curing is needed, it is done as each layer of material is laid down.

12 Navy activities use jetting systems of differing types, making them the second most common system type (Gibson et al., 2010).

a. Advantages

Both subtypes can combine multiple material types; material jetting can use jets of different material at the same time (Niebylski & Rachami, 2013), while binder jetting process allows for many material types to be joined by the disposition liquid (ceramics, plastics, metals) (Gibson et al., 2010). The company Objet sells a jetting system that can print with over 100 materials (McNulty et al., 2012). They are cheaper, faster, and more scalable than other systems. Large jetting machines can have hundreds of nozzles depositing material at the same time (Gibson et al., 2010). Just like their ancestor, the inkjet printer, this means that the product can be made in multiple colors. Supports have to be built, but they can be made of a different material that can be dissolved or washed off after parts build (Gibson et al., 2010).

b. Disadvantages

Binder jetting as some of the same problems as PBF, due to the material bed that has to be maintained for part build. It has to remain level, and the excess material has to be cleaned off after build. For both types of jetting, build resolution and accuracy is not as good as it is for SLA or FDM (with a narrow nozzle), but that is seen as improving as time goes on (Gibson et al., 2010). Nozzles also require cleaning, as they do for the material extrusion processes.

Table 2. Navy AM Modality Summary

	Advantages	Disadvantages	Use Example
Powder Based Fusion	• Can build high quality items in metal, ceramic, polymer and composites • Economical use of build material • No supports needed • Precise	• Complex process • Powder difficult to handle • Expensive • Needs stable environment	• Prototypes • Metal and ceramic end use parts • Molds • Tooling
Material Extrusion	• Simple process • Build in many materials • Easy material handling • Small feed chamber • Low cost	• Nozzle requires cleaning • Most processes need finishing • Material waste from supports • Nozzle sensitive to motion	• Prototypes • Concept models • Polymer parts • Tooling
Vat Photo-polymerization	• High accuracy and finish • Good mechanical properties in polymer parts	• Can only build in resin • 2D build area • Labor intensive post-processing • Products warp and degrade over time • Needs stable environment	• Functional prototypes • Medical devices and models
Jetting	• Simple process • Build with multiple materials at once • Fast • Easy material handling • Scalable • Easily removable supports	• Limited to wax or polymer • Nozzles require cleaning • Low accuracy • Post build cleaning (binder jetting) • Low cost	• Concept models • Sand casting

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IV. DIFFUSION OF ADDITIVE MANUFACTURING

A. ADOPTION IN THE NAVY

Roger’s theory, when applied to AM, has insights as to how the Navy currently treats the technology and the path through which it will diffuse throughout the service. The first people to use the technology in the Navy were rapid prototyping organizations and labs 12 years ago, fitting in the category of “Early Adopters” in Roger’s schema (Rogers, 2003). These engineers and scientists resided in a network of labs as technical specialists that have opinion leadership over other organizations in the Navy. They have high levels of education and saw the benefit of the technology early, but at the same time, used commercially acquired systems when the technology was proven (and cannot take huge financial risks with it), so they cannot be called “Innovators” in Roger’s eyes (Rogers, 2003). NAMTI’s core is personnel of this category, who will use their communications channels to bring the technology the rest of the organization.

Through NAMTI’s plan for the future of AM in the Navy, the means of organizational adoption is going through a change. AM was adopted through collective innovation (Rogers, 2003); the labs and depots that are not all under the same commands within the Navy saw the advantages of the technology and had a consensus that it would work for their purposes. NAMTI’s strategic plan (OPNAV N41, 2014) will be to examine the technology and its efficiencies and then make an authority-innovation decision through its hierarchy in the Navy as a whole for AM to be pushed out through an implementation strategy, planned for 2015 (OPNAV N41, 2014).

The major AM modalities emerged in 1989 (Gibson et al., 2010), but other technologies from that period, such as the personal computer, are now widespread throughout the Navy and DOD, when AM is not. This diffusion difference can be explained with Roger’s five factors, examined in chapter II of this paper. When each factor is examined in depth, the slow speed of diffusion makes sense.

1. Relative Advantage

A majority of the AM technology employment in the Navy up to this point has been in the niche of building one-off prototypes, tooling aids or other unique items. When compared to having a part ordered from an external organization or built in house with subtractive manufacturing means, AM has a moderate to high advantage when compared to the alternative. The speed of the customized manufacture also makes this an attractive option, as does the ability to make parts with structures such as voids and undercuts that are difficult or impossible to mill otherwise.

Onboard ship and with deployed assets, the need for this one-off capability is not as urgent, but that might change as the PTF initiative demonstrates AM capabilities to new organizations. A model for Navy employment could follow the U.S. Army Rapid Equipping Force (REF) mobile expeditionary labs (ELM) that were deployed to Afghanistan in 2012. Deployed soldiers would work with the AM engineers to come up with "good enough" solutions to equipment problems that could not only be used immediately, but also used as a prototype for tooling needed parts from stateside suppliers (Niebylski & Rachami, 2013).

2. Compatibility

AM is highly compatible to how most organizations operate in the Navy. In research and development organizations and depots, it fits perfectly with the need to build prototypes and unique parts; it fits seamlessly in the place that milling and molding equipment currently resides. To commands that do depot level repair and maintenance, an AM machine will an added tool to the machine shop set, and could even replace some of the larger, dirtier, and more cumbersome machines that are currently utilized. Even onboard a deployed ship, it would be a valued technology. A ship that is able to build her own parts has added independence and endurance when compared to one that has to wait for parts from the supply chain. This enables the CNO's "operate forward" tenet and will help mitigate maintenance problems that come with extended deployments. Some thermoplastic build materials are not compatible with Navy standards for fire, smoke, and

toxicity concerns, which mean that that a higher return on investment might come from concentrating on the production of metals and carbon fiber (Print The Fleet, 2014).

3. Complexity

The complexity of AM systems can range from being very elaborate to quite simple and user friendly. Of the four major modalities that Navy organizations use, vat polymerization and powder bed fusion are the most complex; they involve loose material in powder and liquid form, have more environmental concerns and tend to have more post-processing requirements. These factors are not as much of an issue in a laboratory or workshop environment when operated by experienced technicians and engineers.

Jetting and material extrusion machines are much more user friendly and are lower in complexity. All AM systems have PC interfaces to feed the .STL file into the machine for parts build, but the smaller jetting and ME systems can be used akin to a desktop printer; jetting is a direct descendant of inkjet printing, after all.. They are run from an application on computer and the material comes from a cartridge or material feed that is easy to operate. FDM is the popular modality that MakerBot employs for its systems, and would be easily used by deployed personnel with minimal training. PTF is planning to use Stratasys uPrint FDM systems as part of its forward deployment strategy thanks to its relative simplicity (Print The Fleet, 2014). An uPrint system was used onboard the USS Essex this year when it tested AM systems afloat with shipboard personnel (Navy Additive Manufacturing Technology Interchange, 2014).

4. Trialability

AM by its nature has high trialability, regardless of modality. AM’s ease of interface and flexibility allows for experimentation on behalf of the users. The 3D nature of the production, which allows for voids and shapes to be deigned into items, allows previously unavailable design freedom for part production (Weber et al., 2014). An added level of trialability comes from changing the build materials used in the system, so users can see how the machines work with different colors. This directly relates to the complexity of the systems, for if it was complex and confusing to operate, it would deter users from trying to operate it for different products and their associated shapes.

As the industry matures, it appears that is it splitting into manufacturers and processes that focus on low-cost consumer and prototyping markets and high-end processes for direct parts production (Niebylski & Rachami, 2013). The former category solidly favors material extrusion (specifically, FDM) and the latter PBF and vat photopolymerization, with jetting straddling the two. FDM's ease of changing materials is why it is so popular in the prototyping field. In the case of NUWC, they find it easy to change materials for builds with their FDM system, but do not do so for their SLS system. Even though it is capable of using dozens of build materials, it is difficult to change them, limiting them to one material for most of their production (Weber, 2014).

5. Visibility

AM is by nature a low visibility innovation. AM machines reside in workshops or labs; there is nothing inherent to the technology that makes it change how communication between peer organizations and networks. In recent years, it has become more visible in the media, with features published in the *Economist*, *Wired*, and other magazines. The public awareness of the technology and its benefits has been raised due to this, but AM, unlike electric cars, is not something that most people will see or interact with on a daily basis. The strategic planning by OPNAV N41 to manage the technology will make it more visible to Navy decision makers, which will enable its adoption in Navy activities that might not have employed it otherwise (OPNAV N41, 2014).

B. TECHNOLOGY TRANSMISSION PATHS

The current state of AM in the Navy is an uneven use of the technology spread across similar organizations. The labs, warfare centers, and depots are similar to each other in many ways and have been sharing information with each other (and organizations outside the DOD) for years without any formal organization or communication about AM. Roger explains this phenomenon with the principle of "homophily," the degree to which pairs of individuals are similar in certain attributes, such as beliefs, education, social status, and the like (Rogers, 2003). The more organizations or individuals have in common, the more likely they are to interact with each other. Innovations tend to spread quickly in these communities of knowledge or practice.

Table 3. Navy AM Applications by Community (after NAVAIR, 2014; Navy Additive Manufacturing Technology Interchange, 2014; OPNAV N41, 2014; Weber et al., 2014)

	AM modality	Uses	Obstacles
Aviation (NAVAIR, FRCs and NAWC)	• FDM • Jetting • Binder Jetting	• Rapid prototyping • Rapid tooling • Custom parts • Templates	• Flight critical certification • Data rights and IP
Surface (NAVSEA, NSWC)	• FDM • PBF • Binder Jetting • SLA	• Ship models • Seakeeping prototypes • Working prototypes • Shipboard testing • Visual aids • End use parts	• At sea testing (PTF) • Flame/smoke/toxicity qualifications
Subsurface (NAVSEA, NUWC)	• SLA • SLS • FDM • Binder Jetting	• Sand casting molds • Rapid prototyping • Metal repair • End use parts • Industrial tooling	• HAZMAT handling • Flame/smoke/toxicity qualifications
Medical (BUMED)	• SLA • Jetting • Binder Jetting • FDM • Lamination	• Custom medical tooling • Prosthesis • Cranial implants • Surgical guides	• Training with medical personnel

In the Navy, no two organizations are identical, but the spread of AM will happen where there are common needs for such a technology. Ships and other deployable units need parts to operate that are sometimes from obsolete sources or will take a long time to be produce. They also have organizational-level repair capabilities and machine shops for limited parts production. These units are supported by Military Sealift Command (MSC) logistics ships that provide supplies and/or larger warships that have limited depot-level repair and parts storage, such as Aircraft Carriers (CVNs) and Submarine Tenders (AS). The logistics units are in turn supported by Fleet Logistics Centers (FLCs), the SYSCOMs and DLA. Even though each of these organizations is different, they all have the need for parts distribution and some level of repair capability. This flow of material support to the smallest deployed unit illuminates the path that AM technology will spread

in the Navy when it becomes feasible to do so. Right now it is used parts of the largest ashore organizations, but as it is explored as a capability, it will become more and more forward in support of the warfighter.

This future transmission of AM will be fundamentally different than it was in the past. Managers are looking at their innovation ecosystem within their component of this value chain and how it links to others in the Navy and DOD. Under OPNAV N41's leadership, AM will be examined and the risks and benefits of the technology will allow integration to happen where it is most effective. Navy leadership will be able to assess risks holistically and systematically, establish more realistic expectations, develop a more refined set of environmental contingencies, and arrive at a robust innovation strategy (Adner, 2006). As Navy AM branches out from its shore activity based, R&D and depot repair origins, it will have to deal with different considerations than before. The support and supply chain delineated above is not linear, there are "complementary" parts that can support each other laterally and there is commercial industry that can interact with each asset on its own. This means that AM machines will not be needed on every level and with every unit that is a "component" of this innovation chain (Adner & Kapoor, 2010). The Navy needs to look at these interactions from the beginning and their associated challenges as AM systems are adopted.

AM diffusion will take a more top-down or organizationally led nature under OPNAV N41 in concert with NAMTI. A series of cross-functional teams will be introduced at multiple levels in the Navy in order to see where AM capabilities are the best fit. Acting as Roger's "opinion leaders," who have influence on the evaluation of the innovation-decision process and potential Navy units that can be classified as "late adopters" (Rogers, 2003). In most SYSCOMs, they are already at work. At NAVAIR there is an integrated project team that is working to accelerate the introduction of AM, which has become a focus of research, experimentation, and capability investment, based off of Command Level goals (Beal, 2014).

Figure 3. uPrint FDM machine in USS Essex machine shop (from Print The Fleet, 2013)

FDM machines have been pushed to two ships, the USS Essex (Print The Fleet, 2014) as part of CRIC's PTF initiative and the USNS Choctaw County (Hess, 2014a) for NSWC/ONR testing, in order to trial their suitability for afloat operations. Both installations were carried out for different reasons. The work on JHSV was to quantify the environment and effect on the build quality. This was carried out by installing the system in a cargo area while tests were run on the environmental impacts on the part structure and material properties. The primary objective of the PTF initiative was to put a system on the ESSEX and see what the sailors did with the machine and to socialize the concept (P. Hess, personal communication, November 25, 2014). In this case, it was installed in a machine shop onboard and used by shipboard personnel to experiment with the uses of the technology. While the outcomes of these experiments remain to be published, it is an example of an innovation being actively pushed to an asset for experimentation. In both cases, an uPrint office-size FDM system was used to print polymer parts, one of the simplest and most user friendly large commercial systems in the commercial market.

Figure 4. uPrint FDM machine on USNS Choctaw County (from Hess, 2014)

C. OBSTACLES TO ADOPTION

Despite the suitability of AM to the Navy's concept of operations, there are several obstacles that the technology has to overcome in order for it to be fleet-wide usable. Current shipboard production of parts is done in machine ships, where non-critical parts only that do not have intellectual property rights issues are built as needed, but not in large numbers. All other parts are certified and qualified with some level of rigor, but are built off ship and have to be delivered from a depot or the OEM. For AM to live up to its fullest potential, it has to make inroads into that second category.

1. Testing

The Navy and its SYSCOMs are not going to be comfortable with parts being put into ships, aircraft, submarines, and other systems without a level of certification. This is a major hurdle for end use parts built using additive manufacturing. The challenge is setting the proper level of rigor for testing the new AM part; there are millions of supposedly non-critical parts in the DOD (B. Weber, personal communication, September 16, 2014), but they still have to be approved for shipboard use. For example, a bracket that was designed printed, and test fitted successfully on the USS Whidbey Island for the sound powered phone system had to wait one to two years in order for it to be

qualified for installation (J. Lambeth, personal communication, December 1, 2014). It defeats the purpose to have a shipboard AM machine if it cannot print parts that can be used onboard.

On top of the part certification problem, common to any installation of AM machine afloat or ashore, big or small, we must be concerned with the unique environment onboard ship. Even though testing is not complete, early results from the underway use of an FDM system on the USS Choctaw County show layer shifts with roll angles up to 4 degrees and pitch angles up to 5 degrees, which leads to voids in the materials and other structural problems (Hess, 2014). To put this in perspective, on a large surface combatant rolls of that kind are a common occurrence, and are fairly mild compared to the 20+ degree rolls that can be experienced in open ocean. Common to both ships and austere operational locations is the potential for harsh environment part production. Humidity and heavy air pollution can factor into the quality of a part built using virtually any AM technology (Hess, 2014). High temperatures and dusty conditions in the desert present different problems from the air pressure changes and sea salt onboard an underway vessel. All of the above notwithstanding, the materials themselves need to be qualified for building the part and use onboard ship.

A future three-part system could fix this obstacle, if implemented properly, based on the best practices that the Navy currently uses for other systems. First, the AM machine has to be certified by the Navy to build parts, and then routinely maintained or re-certified. If the OEM has standards compatible with the Navy's, this can be done with the service contract instead of a system inspection administered by the Navy. Second, there has to be certified technicians in the Navy, trained to use the AM equipment (including 3D scanners and materials testing systems) to exacting standards. Finally, a centralized data base of .STL files (and linked to the equipment allowance lists) should be approved by the Navy so that exact parts are built to proper tolerances. This system does not resolve unique parts created by the AM systems, so a more rapid procedure to certify new parts will have to be developed.

2. Legal Considerations

There are two broad categories of legal complications to AM diffusion in the Navy. The first is intellectual property. Designing and building a novel part does not break and intellectual property laws, but building a copy of a patented part would (Lambeth, 2014). The grey area comes in-between these two categories. If portion of a part is built, is that infringement? What if a temporary part was built until a genuine part arrives via the supply system? These issues will come up until the Navy comes up a policy based around operational need and are made with parts suppliers. In the future, permission to build a part (at least temporarily) could come with parts and systems contracts, including .STL files that could only be used a limited number of times.

The second legal issue is that of liability. If a part is built by anyone other than the OEM and it fails, who is responsible becomes important to delineate. This is the reason why the above certification system is so important; if the Navy (or a third party manufacturer contracted by the Navy) has a certified operator use an AM machine to build a part to OEM specs from a file given to them by that company and the part fails, it can be blamed on the company. If that “quality chain” is broken in any way, the Navy does not have ground to stand on when part failure happens. A related issue is unique parts. Some systems are more tolerant to parts changes than others, so careful consideration has to be made if a system is “sailor-rigged” with a new AM part that departs from manufacturers specs.

3. Training

The Navy has to have an established system to train operators to use AM systems. PTF has installed a system in the machine shop on the USS Essex, making the enlisted ratings that work in such locations the de facto personnel to work with the system. These ratings (machinist’s mates and machinery repairmen and others) currently operate the lathes, mills, and other conventional subtractive machining equipment and will be needed to be trained to use AM machines. PTF plans to set up an AM training center, this will teach naval military personnel and civilians how to use Computer Aided Modeling (CAD) software, scanners, and various types of AM systems. This course could set the

framework for the development of a certificate program or Navy C-school (Print The Fleet, 2014), important to the “quality chain” mentioned above. This could lead to a NEC (Navy Enlisted Classification) in AM, or even a new rating that works with AM exclusively. Taken further, officers who do intermediate and depot level work (engineering duty officers and aerospace maintenance duty officers) could benefit from similar training so they can supervise such operations and possibly inspect and certify units as part of a qualification process.

Implicit to the diffusion is an information campaign and training seminars to the leaders who will depend on AM to operate, but are not the ones who are the technical specialists. This will prevent potential users who do not know what type of technology would best meet their needs investing in AM equipment. Or redundancy where similar systems are purchased in the naval community when their capabilities could be pooled (Hess, 2014b). Commanding officers and other senior leaders will also have to be convinced that AM parts are as reliable and trustworthy as OEM parts (once they are certified as such). Just like leaders had to be convinced that advances such as steam and nuclear power are capability builders, AM will have to be sold to them. The behavioral “switching costs” of moving to AM has to be overcome; the Navy is locked into a pattern of parts support and limited onsite repair (Geroski, 2003). This links back to Adner’s new-product adoption theory; we have to convince leaders (who are the customers) that the benefits of their innovations so great that they overcome the customer’s overweighing of potential losses (Adner, 2006).

D. ECONOMIC CONSIDERATIONS

AM machines have to be cost effective on a large scale in order for there to be a justification for widespread adoptions. The current niche uses of the technology within the Navy do have that benefit. Labs and depots do not have to waste time and money contracting out for parts or prototype, and generally purchase the material on an as needed basis straight from the OEM, using various purchase vehicles (Beal, 2014). The abovementioned diversity of systems used within the Navy leads to a patchwork of supply support. Each system has its own different support requirements, with the

complexity of AM modality and manufacturer unique designs, making it more complicated. The end demand is low compared to most commodities for each of the materials needed to produce parts (B. Weber, personal communication, September 16, 2014). If the Navy is to adopt this technology wholescale, a cost benefit determination has to be made.

As an example, the two systems tested onboard ships were uPrint SE FDM machines. They cost approximately $34,000 to purchase and have used approximately $12,500 in consumables a year in PTF usage, along with requiring a service contract costing $4,000 a year (Print The Fleet, 2014). Compared to the multibillion dollar budget of the Navy, the cost of putting one such system on each of the around 300 ships (not counting shore facilities) seems to be miniscule, but if the system cannot build useful, effective, and (the catch) certified parts, then it is a pointless expenditure to purchase them on a large scale. Until this happens, the economy of materials stockage and warehousing is infeasible. Furthermore, more and more companies (to follow in the footsteps of paper printing) have microchips in the material cartridges of their systems, requiring material purchases from OEM, and it could void warranties if third party materials are used (Weber, 2014).

More complex and expensive systems cost more to operate than the example but could justify their economic utility more readily. The SLS modality Vanguard si2 2500 can use over $28,000 a year in materials when used at NUWC to build items of varying types (B. Weber, personal communication, September 16, 2014). Items built with these systems are more likely to replace critical alloy and ceramic parts that are difficult to build or machine. Barring significant leaps in adaptability for shipboard use, they will not be adopted in every unit, but could be located at most shore facilities. Until a cost benefit analysis weighing the cost of such systems versus the value of the requisitions (part manufacture plus supply chain costs) is carried out for the entire Navy supply chain, using cost effectiveness as a reason for widespread AM adoption is not founded.

E. MARKET EVOLUTION

As a product, AM is early in its market development. There are many companies competing that sell machines with differing modalities and product features. The market is going through a "shakeout" process wherein a dominant design is created or separate markets offshoot to create AM systems for distinctly different uses and customers, leading to fewer producers of the technology. The outcome of this consolidation process defines the market; it yields a well-defined, widely recognized product, and a small set of associated producers who control the market afterwards (Geroski, 2003). Rather than maximizing performance on any individual dimension of the technology, the dominant design tends to bundle together a combination of features that best fulfill the demands of the majority of the market. (Schilling & Esmundo, 2009).

The process to get to this point is complex and long in the making. Compared to historical examples, it is the time for this shakeout to happen to AM; for eleven consumer goods markets throughout the twentieth century, most of them did not really take off until 20 or 25 years after they were first introduced (Geroski, 2003). This has to happen before the Navy, as a customer determines if AM is cost effective. It is the very early phase market evolution when many different designs are present; the pursuit of economies or learning curves is simply not a smart strategy. The technology is in its fluid phase, there is considerable uncertainty about both the technology and its market, but it is useful in certain niches (Greve, 2009). Much higher premiums are paid to firms who harness the continuing development of the underlying technology to produce better and better designed product variants (Geroski, 2003). The Navy and DOD as a whole can afford to pay higher premiums on a small scale; a few dozen systems in the hands of warfare centers and depots can tinker with the technology, but maturity has to happen before the Navy becomes a customer with hundreds or thousands of systems. The well-defined product that is needed develops from a combination of a demand pull from- and a supply push to- the customers from the producers of AM systems.

The market created for AM systems arose because customers with complementary requirements to the Navy had an "inchoate demand" for the technology. Inchoate demand sets broad priorities or goals which guide innovative activity; it calls forth a variety of

solutions from the supply side (Geroski, 2003), which is the reason there are six major AM modality types; innovation lead to multiple ways to scratch the itch that customers had to be able to make 3D items for rapid prototyping through the combination of existing technologies. “This does not need to be intentional or even the result of foresight or imagination of possible new markets. It could simply be the fulfillment of an [organization’s] motivations and/or an unanticipated consequence of people just experimenting with what is possible and worthwhile” (Dew, Read, Sarasvathy, & Wiltbank, 2011, p. 2). This goes against the idea that a new technology can be found by early on by business leaders with a selection process, it is much more grass roots than that. “Entrepreneurs that use transformation processes produce a larger number of new market ideas than novices schooled in search and selection,” (Dew et al., 2011, p. 4) which is why large companies such as Lockheed Martin and HP are joining the fray now, not at the earlier stages of the technology. Organizations within the DOD are now assisting in this shakeout process; along with industry they are sampling from amongst the different product or service variants on offer, tinkering with the product and learning its value, matching its performance with their gradually better defined sense of need, and communicating the results between themselves and to producers (Geroski, 2003). NAMTI is part and parcel of this process. As the Navy tests AM systems it will determine what is best for certain part types at certain locations, and that will lead to selective acquisition of products, reducing the number of modalities and type of systems deployed fleet wide.

The DOD did not come up with the range and breadth of AM technologies, but now it benefits from these technologies being adapted for military, aerospace, and material development needs. As an organization, the DOD might be unaware of these needs until a new use is demonstrated by a systems manufacturer (Geroski, 2003) For example, the ability to print a part in shapes that were previously infeasible opens up many possibilities for parts replacement and repair. The winners in the selection process are the ones that shine through the explosion of varieties available (Geroski, 2003) and make the DOD and Navy want to invest in their technologies. This is not to say that the government is the only player in the market, there are organizations that have a larger

demand for AM technology that could determine the market for us. What modality GE and other major aerospace companies use to build and repair aviation engine parts will determine what the DOD uses for our aircraft depots- their scale is much larger than ours, and we work closely with such companies, leading to “network effects” assisting our standardization efforts. The choices of many different organizations will be coordinated, for if they are complementary to each other (the DOD buys products from them and repairs them within the organization), the network leads spreads innovations faster than if the activities were disconnected. The Navy is in an excellent position for the network effects to work in its favor. It has a central location in the network (working with multiple other services and commercial companies) and is in close contact with prior adopters, so it can learn about the innovation and judge its value with confidence (Greve, 2009).

At this point, the gains from standardization can lead to better cost benefit analysis outcomes on for the Navy. “In a market where product designs are continually changing, there is always going to be a much greater premium placed on manufacturing flexibility than on manufacturing efficiency. Economies of scale and learning curve advantages can only be exploited when product standardizations has occurred, since they involve making the same product over and over again in large volume year by year, and this creates strong incentives to standardize” (Geroski, 2003). Less expensive systems that are more standardized will make the business case for technology adoption easier to swallow for systems commands, and proven commercialized systems will have more stable pricing and support systems, the reason why we are doing tests with the proven uPrint FDM systems.

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V. FUTURE AM DEVELOPMENTS

A. TECHNOLOGY CHANGES

The process that leads to a dominant design in AM will lead to further changes in the technology. A large number of the disadvantages that each modality has could be negated through improvements to existing techniques or the combinations of current technologies. Laser Engineered Net Shaping (LENS) is one such improvement. Instead of using the bed of powder material substrate that is common to the PBF modality, it uses an arm with multiple nozzles that deposit powder and fuses the material with a laser in a single step (OPTOMEC, 2014). New parts be built with it, but more importantly, it can deposit material directly onto a broken part as part of a repair process, which can then be finished with a subtractive process to bring the part back to its original shape. This has huge implications for depot level refurbishment or repair of parts; instead of replacement of a complex part, additive and subtractive processes are combined to bring the part back to full capability. The results of this technique have been tested to very high tolerances, and it is already in use repairing M1 tanks in Army depots and gas turbine engines (OPTOMEC, 2014).

Improvement to the material extrusion and jetting technologies could combat their restrictions on material use during part build. Jetting uses multiple nozzles to deposit multiple materials at the same time, but material extrusion cannot change materials during the build process. Both modalities could benefit from nozzles that can be rapidly cleaned so that new materials can be introduced in different layers of an item. Even though some jetting systems can do this, they would become more capable or require fewer nozzles to do the job of the current state of the art. If this is too difficult for the material extrusion process, a system that has two FDM nozzles that operate at the same time could make more complex items, with materials added from different angles of varying compositions.

There are many different ways that AM can be improved, but there will soon be a combination of technologies will lead to the widespread dominant design. As early

adopters, DOD labs have started to do this, after all, early adopters add to their advantage by making additional adoptions before many competitors have made their first adoption of the new technology (Greve, 2009). ONR is examining AM technology and testing ways it can be best used in the future, and one of the research areas is "certify as you build" (ONR, 2014, p. 1). This idea has massive potential to combat one of the major hurdles that AM has to overcome. If a part can be scanned or tested during the build process to make sure it is built to end part specifications, the "quality chain" of the part could be a lot shorter. This would involve incorporating sensor technology into the build chamber (and possibly the nozzles, feed chambers, etc.) of an AM system to make sure it stays within temperature and strength tolerances. Another possibility is putting two AM modalities in the same machine. Binder jetting almost fits this category, but the potential of a LENS system that can also put down FDM material could build a whole new range of parts. Of course, there is a lot are a lot of incompatibility issues between the two systems (atmosphere and temperature requirements). If we want this technology onboard ship, we will have to combine AM with stabilizing technology that was first used for weapon and navigation systems. Many of the problems of pitch and roll are negated if the AM system is levelled and mounted with gyro stabilization that has been in shipboard cannon for decades (albeit on larger scale).

B. ENABLING DIFFUSION

In order to reach a future where AM has diffused throughout the Navy, it has to be implemented on a small scale operationally and tested by the late adopter in the system. The current community in which it is employed will spread knowledge to its peers and other like depots and labs, but it has to be demonstrated onboard ship to prove itself as a viable system that can contribute to readiness, or the determination could be made that it is not cost effective in that context.

FDM systems are going are being tested onboard ships with the PTF program, which will also do familiarization and training with operators throughout the Navy. If it seems that the parts that can be built from such systems can only be used for non-critical parts, then they will not be as useful to the Navy, and will not justify the expense of

buying and supporting those systems, let alone training large numbers of personnel to use a system of limited, niche, capability. More pragmatic uses could come from sailors tinkering with the technology that are not currently thought of, and that is reason enough to test it on a small number of ships before it is pushed to more. The community has to see that it is useful and want to utilize it onboard its platforms. The conundrum is that if it is not tested to prove its worth, it might never be employed, but that can be bypassed if ONR and other activities prove its value before it takes up space in a shipboard workshop.

The largest hurdles that have to be overcome are certification and intellectual property. If parts onboard ship can never be used in critical systems, or they cannot pass toxicity or HAZMAT standards, the system will never be used onboard. In addition, companies have to be willing to give up intellectual property rights for the Navy to build parts for most end use systems. If that does not happen, parts will have to be sent to ships anyway, while the AM machines onboard will only be useful for a limited amount of Navy unique designs.

The communities that could best use these systems operationally are the Expeditionary and Special Warfare ones. Following the example that the Army REF set, they could built parts rapidly as needed that do not have to follow aviation, shipboard or undersea tolerances. They can then reach back to manufacturers after the fact and have their improved AM parts built in mass after they test field. The only issue with this from a larger Navy perspective is that this community uses a fraction of the supply chain footprint, so AM will not provide much cost savings in this regard.

C. AM IN THE SUPPLY CHAIN

In the ideal situation, every unit in the Navy to could employ AM systems, with a phased approach that works around many of the obstacles to the technology. If a system fails or is damaged by enemy fire onboard a combatant ship, with multiple parts needing replacement, it would first turn to its organic AM systems for parts manufacture. Sailors onboard who are qualified by NEC, or an new rate such as “Additive Machinist” or “Additive Repairman” would build pre-certified parts from a .STL database on their unit

level AM systems. Requisitions would then be sent out for whatever parts they are not certified to build.

The parts requisition would then go to the next most capable unit to leverage its AM capabilities. In the case of a Carrier or (Expeditionary) Strike Group this would be the CVN or LHA sailing in company, or an AS nearby. Onboard these larger vessels are limited intermediate level repair facilities that would be much better equipped for parts manufacture and repair. Larger, higher end AM systems and complementary testing equipment would be installed in their shops, supervised by Engineering Duty Officers and/or Aviation Maintenance Duty Officers who are able to certify parts to higher standards. In concert with more experienced sailors and civilian technicians, these officers would be have the training to deal with technical and copyright issues, and the information systems onboard these ships could communicate with part OEMs, who would allow parts build to go through with licensing permission, or not release firmware for electronic systems until the Navy pays for it. This personnel structure is not unlike how medicine is currently done onboard deployed assets; Independent Corpsman are only qualified to carry our certain medical tasks, failing that, patients are sent to larger vessels with officers Doctors and Surgeons for more complex procedures. The larger asset would then send the parts it build back to the smaller asset it is supporting and continue routing the parts that are beyond its capabilities.

Next, forward bases in theater or activities such as FLCs that could employ even higher level systems in workshops would be used. These AM systems could be containerized for easy movement and upgrade in theater. Even with future advances, there will be systems that will not be suited for shipboard use, due to motion and atmospheric considerations. Being located in the vicinity of the ships they support, they could manufacture parts much closer to deployed units than CONUS and ferry them out to ships via logistics assets. If parts are small enough, they could be sent out via small logistics VTOL UAS (drones). Independently deployed small ships would get critical parts in a fraction of the current time this way, even without the support of a large deck and their facilities. In a DOD-wide context, Army units would skip the intermediate large

deck step and get AM from a base larger than the Forward Operating Base (FOB) if they could not build the parts themselves.

The pinnacle of this AM employment method would be CONUS AM plants. They would be contractor run or government run centralized facilities that employ dozens of systems of differing modalities. Equipped with certifying equipment and pre-built component parts that are difficult to build such as transistors and batteries, they would be able to build 95% of parts that are on Navy ships, then hi-priority ship them to requesting units. In the current support structure, when an obsolete, low fail part that is a component of a legacy system onboard ship fails, it can take weeks or months to be built, especially if the original manufacturer has gone defunct (a problem in older ships and ships in small classes). The ability to build these parts, even stateside, would increase readiness significantly throughout the fleet. These plants would also support units that are CONUS for training, or in maintenance periods.

DLA can have important contribution to all four of these tiers in different ways. Contracting support would be useful for all of the above units, and that is the first place where DLA should get involved in AM diffusion. Each step of this process requires service and software subscription support, along with differing levels of build material purchasing. Once the demand of certain AM materials is stabilized and predictable, especially for the larger land based AM shops and plants, DLA can stock AM materials in bulk in order to realize cost savings for DOD as a whole.

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VI. CONCLUSION

DLA needs to be ready for a dominant AM systems to be chosen, considering that it already has the support structure in place. DLA Troop Support and Construction supply chain has awarded regional CONUS and OCONUS indefinite delivery/indefinite quantity contracts for world-wide support of Facilities Maintenance, Repair, and Operations (MRO) supplies (DLA Troop Support Construction and Equipment, 2014). Even though AM materials are not currently supported by this program, they fit in the military class of supply for repair parts support (class IX) that is covered by this DLA office. If the OEM of an AM machine requires contracts for support of their proprietary systems and their supplies, there is an existing program that can expand into that requirement. The MRO contracting program provides direct delivery to the ordering activity (DLA Troop Support Construction and Equipment, 2014), and would allow the DOD to negotiate large contracts, benefiting from economy of scale. Indefinite Delivery/ Indefinite Quantity (IDIQ) contracts could be set up with this program that could include full systems along with the more popular consumables (both machine and materials) and services (such as repair and upgrades) (B. Weber, personal communication, September 16, 2014). Another route that could be taken is a service-style contract with the manufacturer, especially well-suited for larger machines located in fixed locations. DLA could pay for the AM system in a "per hour" or "per volume of material used," not owning the physical machine, per se. However, this would be very difficult for the implementation of AM machines for forward-deployed units, unless there were embedded OEM reps capable of providing the service (a situation that already happens at large bases and on large ships).

AM technology, if fully implemented in the DOD, could lead to smaller physical warehousing and distribution depot requirements. If the above contacting mechanism is used, materials will be delivered to the end user directly in most cases, but at the worst, might have to spend very little time in distribution centers overseas before being routed to operational units. In the event that DLA's customers settle on a limited number of AM systems and use them in a supportable pattern, DLA could buy materials in bulk and store them in its warehouses. Even though some AM systems can use hundreds of different

build material of differing composition and color, this would still save space and money for DLA warehouses and depots; instead of hundreds of thousands of items that have to be stocked and replenished, there would be a fraction of that amount of AM line items. Fewer line items mean fewer bin locations in distribution centers and that requires fewer personnel to maintain inventory. Contracting requirements would also be diminished, instead of dealing with the multitude of companies that produce parts for the DLA supply chain, large quantity contracts could be made with the AM technology manufacturers. These benefits accrue only if AM technology is able to replace a large portion of parts that the DOD needs for operations. If the above obstacles to adoption are not overcome and AM has to remain a niche, materials for those systems will just add to stocking requirements without replacing a large majority of other inventory.

DLA should begin to advertise the capability to support AM operations through the MRO program immediately. This reduces the complexity of the adoption by making it easier for activities to get supplies through an already established system. The contracting support of AM operations would save money and then cause a positive feedback loop leading to further diffusion and greater network effects in DLA customers. AM is already in use in the DOD on a small level, and in less than five years, there will be dozens of more systems for DLA to support. When OPNAV N41 releases reports and guidance on the technology, decision leaders will be better informed of the uses of AM, and it will be further employed in the Navy due to top-down direction and personnel training programs such as PTF.

In order to be ready for the future of AM in DOD, further research is needed in a number of areas. Most importantly, each service needs to do a cost accounting of AM use. There is no central collection of cost and usage figures for AM systems and the materials that they require. In the process of writing this project, limited data on the activity level could be collected, but a larger scale collection process is in its infancy. In order to come up with best practices for efficiency gains (such as reducing the number of different systems in DOD), this information needs to be collected, and a process that NAMTI has already begun for the Navy. In addition, the cost benefit of purchasing AM built parts through a contractor needs to be examined. Is it more cost effective to have

private companies build the parts and ship them to DOD units, or should the military pay for the systems and required training needed to build a majority of the parts it needs?

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